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Extraction of mechanical properties of foot plantar tissues using ultrasound indentation associated with genetic algorithm

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Abstract This paper demonstrates the use of ultrasound indentation technique for estimating the mechanical properties of foot plantar tissues in virtue of the reconstruction of the force response using genetic algorithm (GA) from an indentation test based on a quasi-linear viscoelastic (QLV) model. The indentation test on the plantar tissues covering the right first metatarsal head of a normal subject was carried out to verify the feasibility of the GA for the extraction of the tissue properties. The QLV properties of the plantar tissues were determined by the GA with a fixed Poisson's ratio. Such results were then compared with those obtained using a classical optimization method. Moreover, the GA was further employed to simultaneously determine the QLV properties as well as the Poisson's ratio of the plantar tissues. The correlations between the QLV properties and the Poisson's ratio are discussed.

Introduction

Foot ulceration is one of the most significant complications of diabetes mellitus (DM) [1]. Assessment of interfacial plantar pressure is crucial for the prevention and treatment of diabetic foot ulceration as diabetic ulcers frequently occur at pressure sensitive sites, under the bony prominences of the metatarsal heads (MH) and calcaneus [2]. Based on the plantar pressure, suitable footwear can be designed to distribute plantar pressure properly in daily activities of DM patients [3–5]. In particular, investigation on the mechanical properties of plantar foot tissue is the first step in plantar pressure assessment.

Various mechanical methods such as indentation, compression, tension and torsion, have been developed for the assessment of the tissue mechanical properties in the past decade [6, 7], in which indentation is the one of the most popular approach. No special requirement of the sample size and the capability of the in situ or in vivo measurement are the two main reasons to make indentation attractive. Mechanical properties of the tissue can be extracted from the force-deformation relationship obtained by the indentation test quantitatively. Ultrasound (US) indentation, comprised of US and indentation measurements, is comparatively easy to use for in vivo measurement of the stiffness of soft tissues such as articular cartilages [6, 8, 9], residual limb tissues [10, 11], fibrotic neck tissues [12, 13], as well as diabetic plantar tissues [14]. With the tissue thickness measured together with the force-deformation relationship obtained in the US indentation, mechanical properties of the tissue can be estimated using various theoretical models. Zheng et al. developed a US indentation system with a pen-size probe to investigate the thickness and Young's modulus of plantar tissue of both healthy and elderly diabetic subjects [14]. In this preliminary study, only elastic properties of the plantar tissue were considered by controlling the indentation rate and depth and assuming that the tissue was nearly incompressible, i.e. Poisson's ratio was taken as 0.45. It was found that the plantar tissues of the DM patients were significantly stiffer and thinner than those of the unimpaired subjects. Further studies on the viscoelastic

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properties of the plantar tissue without the incompressibility assumption are necessary.

By neglecting the non-linearity and viscosity of the soft tissue, a linear elastic model [15] was employed to derive the effective stiffness [6]. However, pervious studies [13] revealed that non-linear viscoelastic properties of the soft tissues have been noticed during the indentation tests. The assumption of the linear elastic behaviour of the soft tissue may not be always valid, especially under a large strain condition. As different indentation rates may affect the estimation of effective stiffness, measurement errors of the stiffness can occur in results. In consideration of the non-linear viscoelastic properties of soft tissue, a quasi-linear viscoelastic (QLV) model has been introduced to describe the response of the soft tissues during a cyclic-loading indentation test [13]. To extract the QLV parameters (Young's modulus, time constant and viscosity-related constant) from the indentation test, classical iterative process was used to optimize the indentation data based on the QLV model [13]. Poisson's ratio is a material parameter representing the ratio between the extension/compression in the axial direction and the contraction/expansion in its cross section [16]. A constant Poisson's ratio in the range of 0.3–0.5 has been widely accepted to study the elastic properties of soft tissues [15, 17–19]. However, cautions have to be taken when this assumption is applied over different body sites, in patients with different diseases and ages since the Poisson's ratio may vary from individual to individual and from site to site. Moreover, assumption of the same value of the abnormal tissue as that found in the normal case may be inappropriate. The versatility of the QLV parameters may probably be limited by which the Poisson's ratio is constrained for the optimization process. As a result, the QLV parameters with a fixed Poisson's ratio may not truly reflect the real condition of the tissues.

Targeted at determining the QLV parameters as well as the Poisson's ratio of foot plantar tissue, genetic algorithm (GA) was exploited to solve the optimization problem based on the ultrasound indentation data combined with the QLV model in this paper. The feasibility of the GA for extracting the mechanical properties of the plantar tissue is demonstrated by virtue of testing the normal plantar soft tissues covering the first metatarsal head of the right foot using ultrasound indentation. By using the GA, the QLV parameters together with Poisson's ratio of the plantar tissue can be estimated simultaneously.

Methodology

Ultrasound (US) indentation

The ultrasound (US) indentation system used in the present study mainly consists of a hand-held indentation probe (Fig. 1) and a US pluser/receiver. Tissue ultrasound palpation system (TUPS) can be connected to a personal computer via a part of universal serial bus (USB) to display and process the collected data in real time [4]. The probe has an unfocused 5 MHz US transducer at its tip in-series with a 10 N load cell. The flat-end transducer with 9 mm diameter functions as a US emitter, receiver and indenter concurrently. The thickness and the indentation depth of the soft tissue were determined from the flight time of the ultrasound signal that reflected from soft tissue-bone interface [6] associated with the sound speed in soft tissue, i.e., 1540 m/s [20]. The force response and the US signal were captured during the indentation test simultaneously with approximately a rate of 25 frames per second. The ultrasound signals were sampled at a rate of 100 MHz. Three cycles of loading and unloading with approximately 8 s duration were carried out for each indentation trial. As the indentation rate was controlled around 0.5 mm/s, a stable manual indentation could be assumed [21].

Estimation of soft tissue properties

The force-deformation curves with three cycles of loading and unloading were obtained from the indentation test. To estimate the mechanical properties of the soft tissue, a quasi-linear viscoelastic (QLV) model was used to fit the load-deformation curves [13]. By neglecting the viscosity of the soft tissue, the indentation force can be expressed as,

$$P(u) = \frac{2ah\kappa(u)}{1-\nu^2} Eu, \quad (1)$$

where a and h are the radius of the indenter and the original

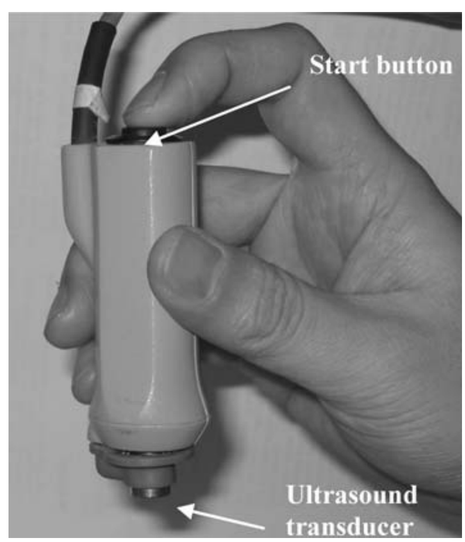

Fig. 1 The indentor of ultrasound (US) indentation system used in current study

tissue thickness respectively. v is the Poisson's ratio of soft tissue, $u = w/h$ was defined as the indentation ratio in which w is the applied indentation depth, κ is a scaling factor that only depends on u for an indentation with given thickness and Poisson's ratio [22], and E is the Young's modulus of the soft tissue. If the viscosity of soft tissue is taken into account, an instantaneous Young's modulus in the QLV form is written as [23],

$$E(u,t) = E^{(e)}(u) \cdot G(t), \quad (2)$$

where $E^{(e)}(u)$ is the un-relaxed elastic modulus and $G(t)$ is the reduced relaxation function for which $G(0) = 1$ [23]. To sake for simplicity, these two functions are proposed as the following forms in this study, i.e.,

$$E^{(e)}(u) = E_0 + E_1 u \quad (3)$$

and

$$G(t) = 1 - \alpha + \alpha e^{-t/\tau}, \quad (4)$$

where E_0 is the initial modulus, E_1 is the non-linear factor, τ is the time constant and α is the viscosity-related constant. By proceeding the data reduction process [24], the force response at any discrete time I can be reconstructed from the indentation history $u(j)$, i.e., $1 \leq j \leq i$ as,

$$P(i) = \frac{2ah}{1-v^2}\left[\kappa(u(i))\left[E_0 u(i) + E_1 u^2(i)\right] - \frac{\alpha}{\tau}\sum_{j=1}^{i}\kappa(u(i-j))\left[E_0 u(i-j) + E_1 u^2(i-j)\right]e^{-j\cdot\Delta t/\tau}\Delta t\right] \quad (5)$$

where Δt is the time interval between two adjacent data points, $\kappa(u(i))$ can be found in the kappa's tables according to corresponding aspect ratio (a/h), Poisson's ratio (v) and indentation deformation (w/h) [20] by interpolation and extrapolation.

Extraction of the mechanical properties of soft tissue can be obtained by solving the optimization problem about minimizing the root mean squared (RMS) error between Eq. (5) and the load-deformation data obtained experimentally. This RMS error is expressed as,

$$S_{err} = \sqrt{\frac{\sum_i (P_s(i) - P_e(i))^2}{\sum_i (P_e(i))^2}}, \quad (6)$$

where $P_e(i)$ and $P_s(i)$ are the experimentally and numerically simulated force sequences respectively.

Genetic algorithm (GA) [25], instead of classical optimization methods [13], is proposed in the current study to tackle this optimization problem. In comparison with the classical optimization methods, GA requires no gradient information and produces multiple optima rather than a single, local optimum, making it to be a powerful tool for solving various optimization problems. Five major operations of GA including encoding, evaluation, selection, crossover and mutation have been described in details [25]. Only the definition of an objective function is necessary for GA to solve this problem. The objective function in this case is to minimize the RMS error as shown in Eq. (6). An overview of GA for extracting the mechanical properties of soft tissue is schematically presented in Fig. 2 and the corresponding parameters of running GA are given in Table 1. It is noticed that the number of mechanical parameters of soft tissue can be easily adjusted in the GA program.

Experimental validation

Subject, site and posture

A male healthy subject with an age of 22 was recruited for this study. The subject does not have any plantar tissue lesions or other skin problem. The plantar tissue covering the right first metatarsal head was chosen for the test, as

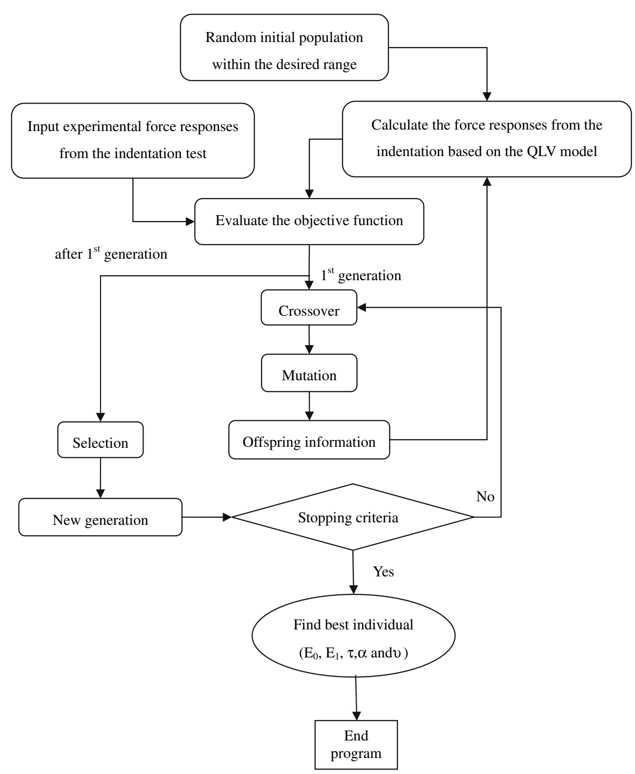

Fig. 2 An overview of GA for extracting the mechanical properties of soft tissue

Table 1 The corresponding parameters of running GA for extracting the mechanical properties of soft tissue

GA setting					
Number of population	800				
Number of variables	4 for the fixed Possion's ratio, 5 for searching Possion's ratio				
Range of variables	E_0 (kPa)	E_1 (kPa)	τ	α	V
Upper limit	0	0	10^{-6}	0	0.3
Lower limit	1000	1000	10	1	0.5
Precision of binary representation	E_0 (kPa)	E_1 (kPa)	τ	α	v
	10	10	10	7	5
Generation gap	0.9				
Stopping criteria	more than 80% population with the same value of objective function				

shown in Fig. 3. The subject was asked to sit on the fixed chair and keep relaxed, because the muscle contraction significantly affects the experimental results [23]. The knee was kept in fully extension and supported by the foot stand. Marker was used to indicate the anatomical location of first metatarsal head of the right foot [14].

Testing procedure

Ultrasound couplant gel was applied on the testing site before the measurement in order to make sure that the US signal could propagate through the contact gap. By loading and unloading the probe on the testing site for a few times, the plantar tissue was preconditioned. Afterward, the probe was held in an optimal alignment in order to capture a maximum US echo signal reflected from a soft tissue-bone interface. Finally, the indentation test could then be started. A demonstration of the indentation test is shown in Fig. 4.

During the measurement, the probe was first located at the testing site with a minimal force and then manually loaded and unloaded the testing site gradually for three cycles in each trial. The indentation rate was controlled approximately at a rate around 0.5 mm/s by monitoring the visual feedback of the indentation response displayed on a computer monitor. Slippage of the probe must be avoided throughout the test. The maximum indentation depth was controlled at 10% of the initial thickness. There were three trials in this experiment and a two-minute rest was allowed between every trial for the tissue to return to the original state.

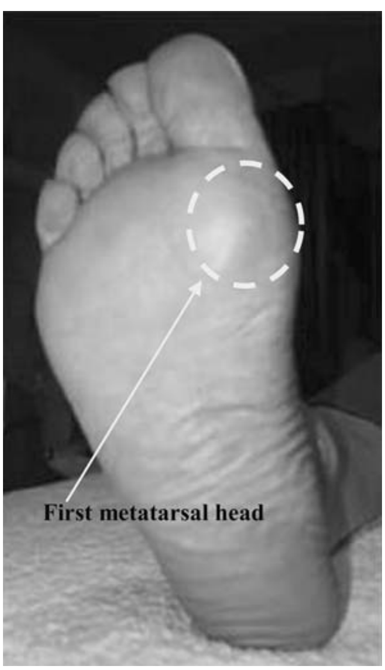

Fig. 3 The right first metatarsal head of the subject

Fig. 4 A demonstration of the indentation test

Results and discussion

Force-deformation loading-unloading curves for the first metatarsal head of the right foot obtained by the indentation test are plotted in Fig. 5. From this figure, an obvious discrepancy between the phases of loading and unloading curves indicated that the typical hysteresis phenomenon involved in the viscoelastic behaviour. Based on the indentation history, the material properties of the soft tissue can be extracted by fitting the force-deformation curve. Before using the GA to search the material properties, the capability and reliability of using GA in finding out the mechanical properties of soft tissue was studied by comparing the optimization results obtained with GA and a classical optimization method using a Matlab build-in function [13]. Note that the initial values for searching the optimal material constants were necessarily set before the classical optimization process and these initial values were followed by the pervious experimental findings [12]. In contrast, no initial value was compulsory for the GA and only the ranges of the parameters defined as indicated in Table 1 were needed. That means the GA can function probably without knowing the previous experimental data. In this case, only the QLV parameters were extracted from the experimental results with a fixed Poisson's ratio (v = 0.45). The optimization results obtained from the GA in trial 3# are shown in Fig. 6a–d. All QLV parameters converged to a constant value within 40 generations, which were corresponding to the optimal QLV parameters of the planar tissue covering the right first metatarsal head of the subject.

Table 2 lists the QLV parameters obtained by the GA and the classical optimization method. The mean percentage RMS errors obtained from the GA and the classical optimization method are comparable. For the QLV parameters, the mean initial modulus E_0 and non-linear factor E_1 were estimated as 5.72 ± 1.71 kPa and 41.37 ± 10.40 kPa, respectively using classical optimization. By using the GA, which are only less than 10% difference compared with the one calculated by the classical optimization method. However, the percentage differences of the mean time constant τ and the mean viscosity-related constant α between these two methods are approximately 15%. It is noticed that the standard derivation of the QLV parameters of the GA is lower than that of the classical one. Therefore, it can be concluded that the results obtained by GA are not only comparable with, even more precise and reliable than the classical method.

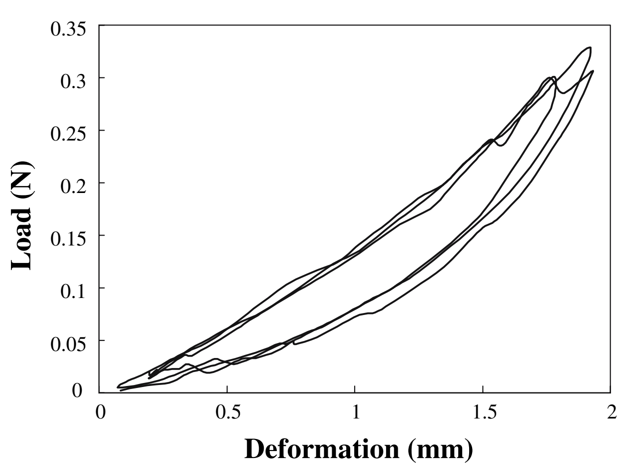

Fig. 5 Force-deformation loading-unloading curves for the first metatarsal head of the right foot obtained by the indentation test

Figure 7 shows the force indentation history and its curve fitting results obtained using the GA for trial 3#, where the value of the Poisson's ratio was also optimized simultaneously. The simulated force well correlated with the measured force with the mean percentage RMS error of 0.076 ± 0.03 for all trials. This error is a little lower in a comparison with the error obtained from the pervious results with the fixed Poisson's ratio. The reason is that more variables could increase the degree of freedom for the curve fitting of the QLV model. This implies that the GA is able to search the QLV parameters as well as the Poisson's ratio in parallel. Fig. 8a–e illustrate the convergence of the GA for searching the QLV parameters and the Poisson's ratio. Only less than 70 generations is necessary to get the converged results of these parameters.

The optimal QLV parameters and the Poisson's ratio extracted using the GA is listed in Table 3. The mean values of the initial modulus E_0, the time constant τ and the viscosity-related constant α are very close to that found in the searching process without involving the Poisson's ratio as indicated in Table 2. On the other hand, the mean of non-linear factor E_1 of 36.49 ± 7.40 kPa in the 5-variable case is lower than the one (41.06 ± 9.33 kPa) obtained from the 4-variable case. The mean of Poisson's ratio is equal to 0.47, which is a little higher than the value (0.45) based on the pervious assumption [12, 13]. Referring to Fig. 8b and d, it is interestingly observed that E_1 is in a correlation with v during the searching process of the GA as these two parameters increase and decrease at the same generation. Comparatively, no such correlation is seen in searching other parameters as indicated in Fig. 8a–d. It can be concluded that the Poisson's ratio has no apparent influence on E_0, τ and α. However, it affects E_1 significantly.

Conclusion

The mechanical properties of foot plantar tissues were extracted from the force-deformation relationship of the

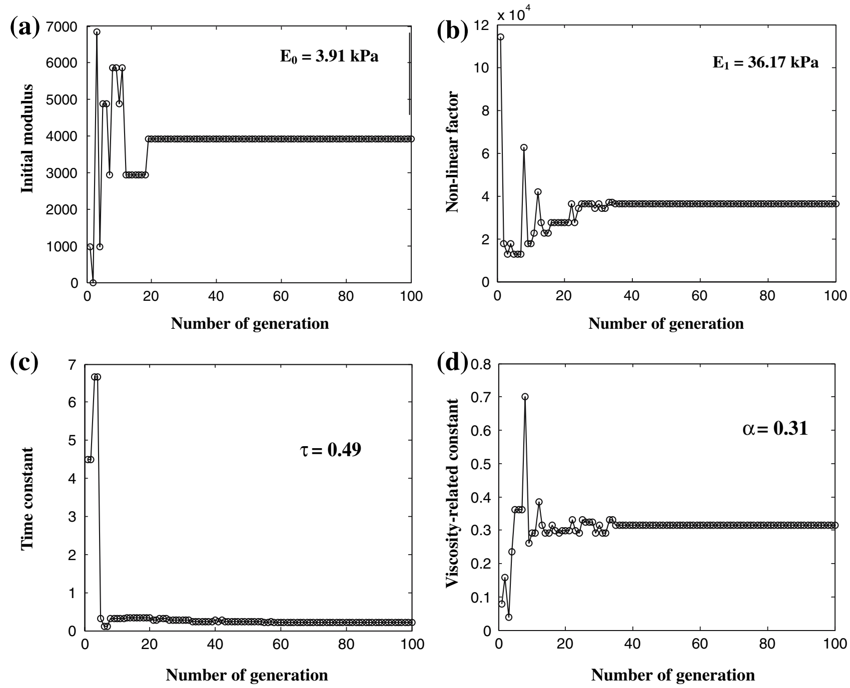

Fig. 6 The optimization results of (**a**) the initial modulus E_0 (**b**) the non-linear factor E_1, (**c**) the time constant τ, and (**d**) the viscosity-related constant α obtained using the GA for trial #3 with fixed Poisson's ratio

Table 2 The QLV parameters obtained by the GA and the classical optimization method in 4-variable case

QLV parameters		S_{err}	E_0 (kPa)	E_1 (kPa)	τ	α
Optimization method						
Trial 1#	GA	0.051	5.87	51.81	0.25	0.51
	Classic	0.054	7.44	53.24	0.61	0.19
Trial 2#	GA	0.109	5.87	35.19	0.44	0.44
	Classic	0.110	5.71	33.85	0.39	0.50
Trial 3#	GA	0.067	3.91	36.17	0.49	0.32
	Classic	0.068	4.02	37.03	0.34	0.40
Mean	GA	0.076	5.22	41.06	0.39	0.42
	Classic	0.077	5.72	41.37	0.45	0.36
SD	GA	0.030	1.13	9.33	0.13	0.10
	Classic	0.029	1.71	10.40	0.14	0.16
Percentage difference (%) between two optimization methods		1.30	8.74	0.75	13.33	–16.66

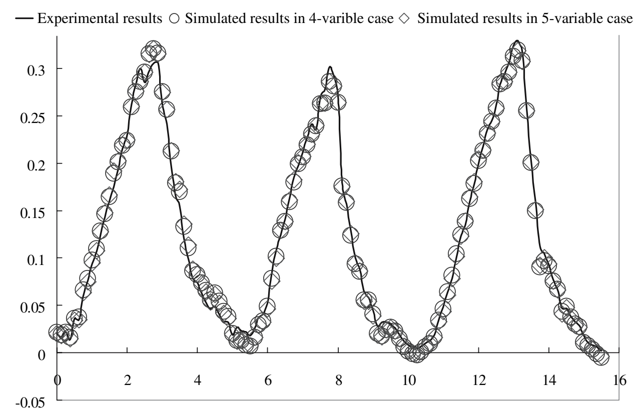

Fig. 7 The force-indentation history and its curve fitting results obtained using the GA for trial #3 included searching the Poisson's ratio

ultrasound indentation tests based on the QLV model by means of reconstructing the force response using GA. The QLV parameters and the Poisson's ratio were determined by minimizing the RMS error between the simulated and experimental forces. The feasibility of using the GA for determination of the tissue properties was validated by the indentation test of the planar tissue of the right first metatarsal head from a normal subject. Force-deformation curves of the subject captured from the indentation test demonstrated the viscoelastic behaviour of the soft tissue. Moreover, the capability and the reliability of the GA for extracting the mechanical properties of the soft tissue were verified by a classical optimization method with a fixed Poisson's ratio. It was revealed that the GA was able to give higher precision and reliable results than the classical optimization method. The QLV parameters and the Poisson's ratio were successfully optimized by the GA simultaneously. Compared with the case that with the fixed Poisson's ratio, the mean values of the initial modulus E_0, the time constant τ and the viscosity-related constant α are approximately the same, however, the mean of non-linear factor E_1 became lower. The mean of Poisson's ratio ν was

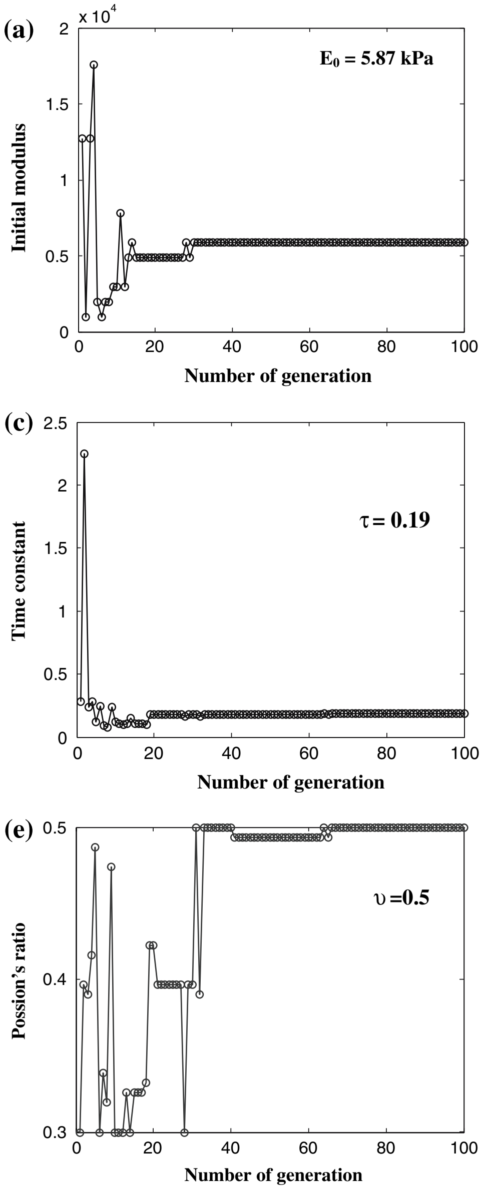

Fig. 8 The optimization results of (**a**) the initial modulus E_1, (**b**) the non-linear factor E_1, (**c**) the time constant τ, (**d**) the viscosity-related constant α and (**e**) the Poisson's ratio v obtained using the GA in trial #3 included searching the Poisson's ratio

Table 3 The optimal QLV parameters and the Possion's ratio were extracted from the QLV model using the GA

QLV parameters	S_{err}	E_0 (kPa)	E_1 (kPa)	τ	α	v
Trial 1#	0.047	5.87	44.97	0.19	0.61	0.5
Trial 2#	0.111	5.87	33.24	0.47	0.42	0.45
Trial 3#	0.069	3.91	31.28	0.42	0.32	0.47
Mean	0.076	5.22	36.49	0.36	0.45	0.47
SD	0.033	1.13	7.40	0.15	0.15	0.03

found to be 0.47, which agreed with the pervious experimental results. In particular, a correlation between E_1 and v was exhibited during the searching process of the GA.

The present US indentation technique associated with the proposed data analyzing methodology will be further employed for the assessment of the viscoelastic properties of the diabetic foot plantar tissue. Consequently, the viscoelastic properties of the foot plantar tissues from healthy and diabetic patients can then be compared. It is very important for the plantar pressure measurement in order to evaluate the danger of ulceration of diabetic foot, to help the management of ulceration, and to facilitate the design of foot orthoses.

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